GiBUU – A Theory and Method for Neutrino-Nucleus Interactions

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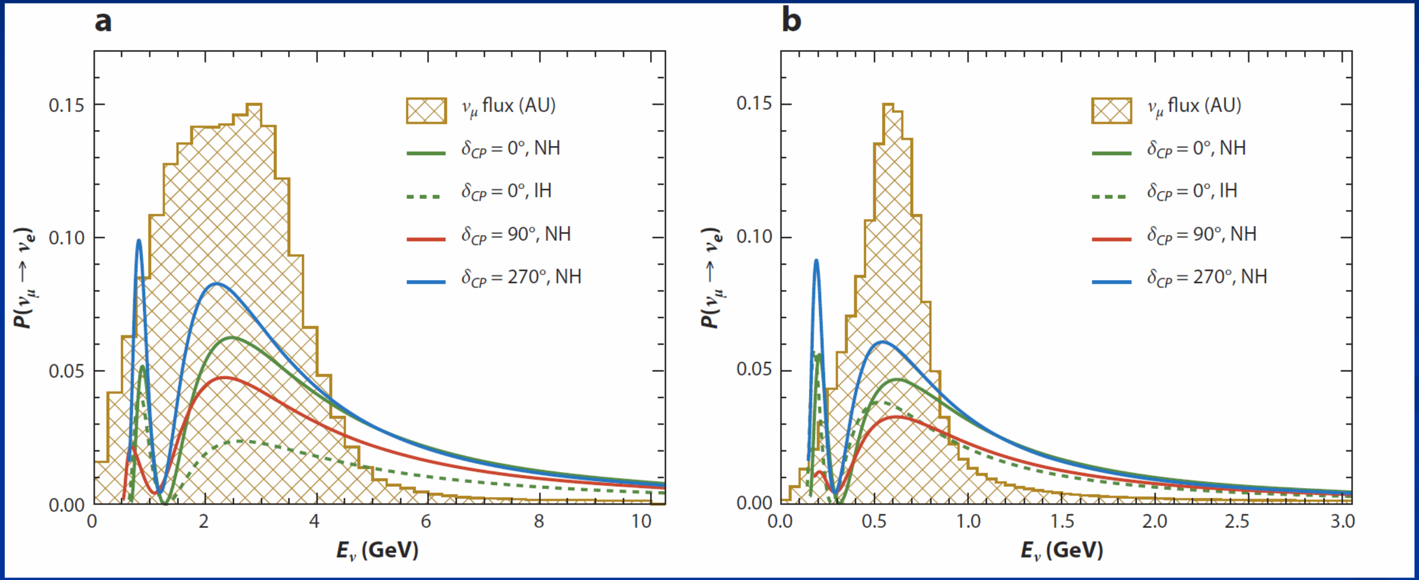
Motivation

Oscillation Signals as $F(E_\nu)$



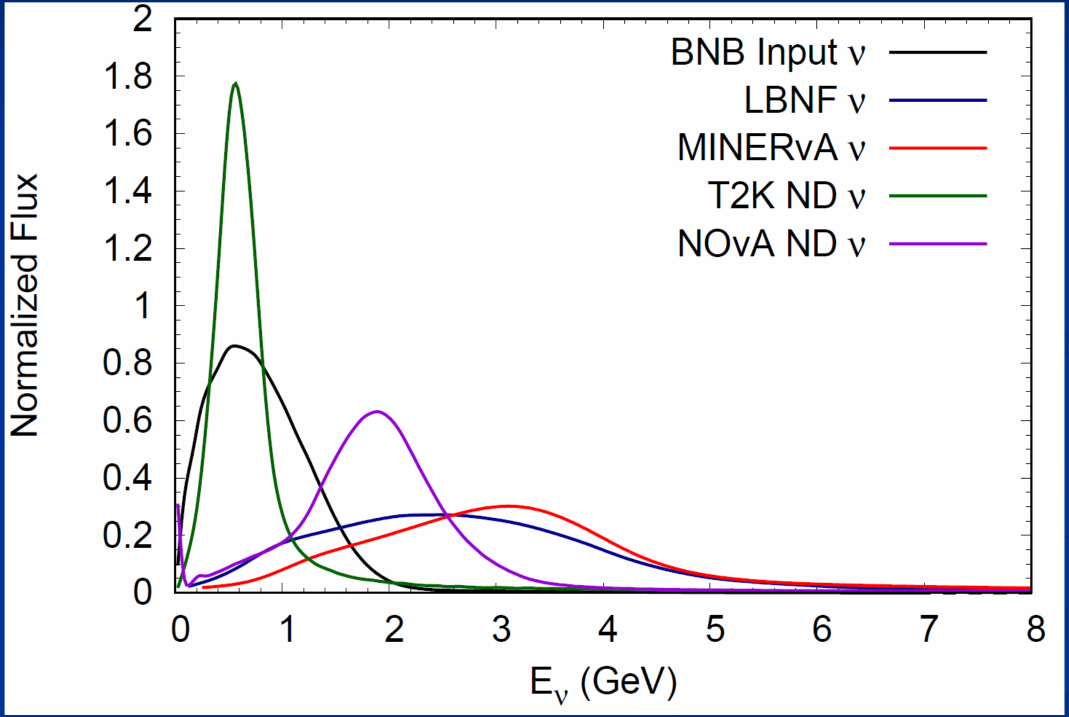
From:
Diwan et al,
Ann. Rev.
Nucl. Part. Sci 66
(2016)

DUNE, 1300 km HyperK (T2K) 295 km

Energies have to be known within 100 MeV (DUNE) or 50 MeV (T2K)

Ratios of event rates to about 10%

Energy-Distributions of Neutrino Beams



Energy must be reconstructed event by event, within these distributions

Energy Reconstruction

- Need neutrino energy to extract neutrino mixing angles and δ_{CP}, but how to get it??

- Only way: from the final state!
  → Need cross sections for initial interaction *and* final state interactions

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Cross Sections

Neutrino Cross Sections

- All targets in long-baseline experiments are nuclei: C, O, Ar, Fe
- Cross sections on the *nucleus*:
  - QE + final state interactions (fsi)
  - Resonance-Pion Production + fsi
  - Deep Inelastic Scattering → Pions + fsi
- Additional cross section on the *nucleus*:
  - Many-body effects, e.g., 2p-2h excitations
  - Coherent neutrino scattering and coh. pion production

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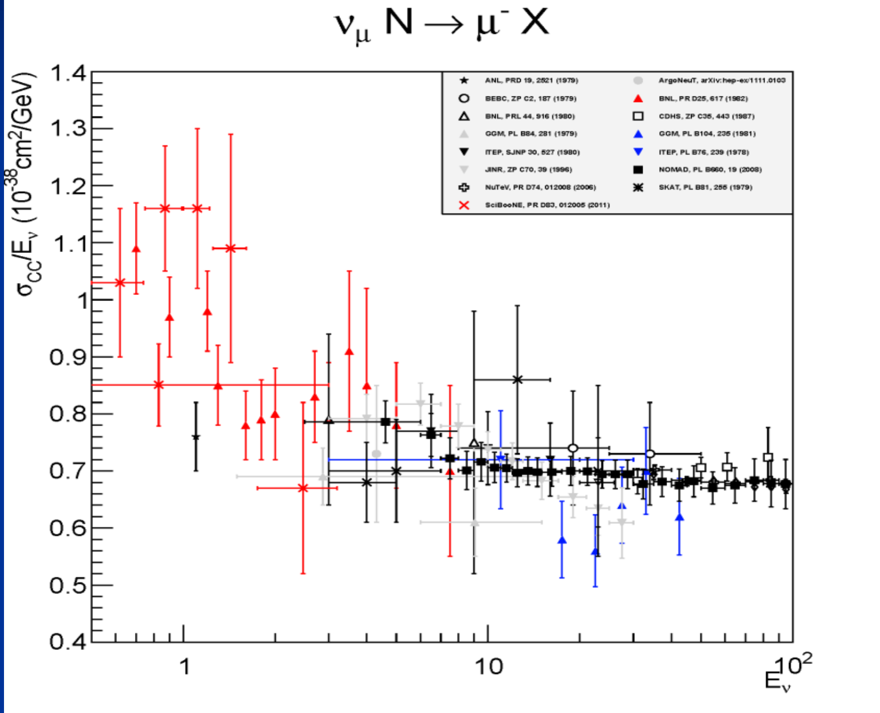
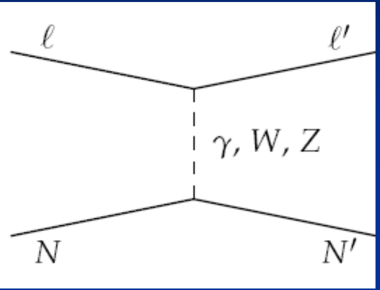
Neutrino-Nucleon Cross Sections

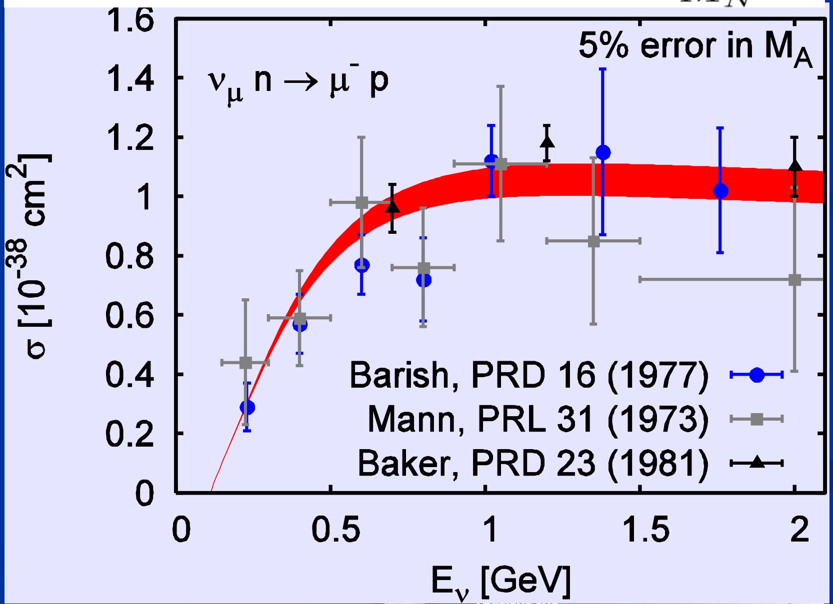


Experimental error-bars directly enter into nuclear cross sections and limit accuracy of energy reconstruction

Quasielastic Scattering



$$J^\mu_{QE} = \left(\gamma^\mu - \frac{\not{q}\, q^\mu}{q^2}\right) F_1^V + \frac{i}{2M_N}\sigma^{\mu\alpha} q_\alpha F_2^V + \gamma^\mu \gamma_5 F_A + \frac{q^\mu \gamma_5}{M_N} F_P$$



- Vector form factors from e–scattering
- axial form factors

  $F_A \Leftrightarrow F_P$ and $F_A(0)$ via **PCAC**

  dipole ansatz for F_A with

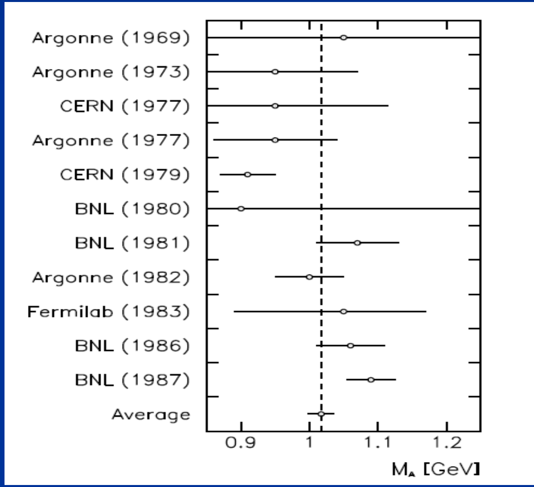
  M_A= 1 GeV:

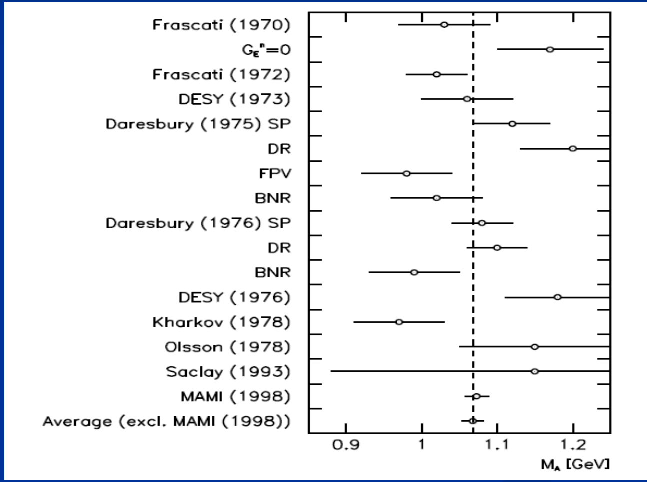
$$F_A(Q^2) = \frac{g_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$

Axial Formfactor of the Nucleon

- neutrino data agree with electro-pion production data

Bernard et al, J.Phys. G28 (2002) R1-R35





$M_A \cong 1.02$ GeV world average

$M_A \cong 1.07$ GeV world average

Are there still neutrino generators out there with $M_A = 1.3$ GeV???

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Pions

- Pion production amplitude
  = resonance contrib + background (Born-terms)
- Resonance contrib
  - *V* determined from e-scattering (MAID)
  - *A* from PCAC ansatz
- Background:
  - Up to about Δ obtained from effective field theory
  - Beyond Δ unknown
  - 2 pi BG totally unknown

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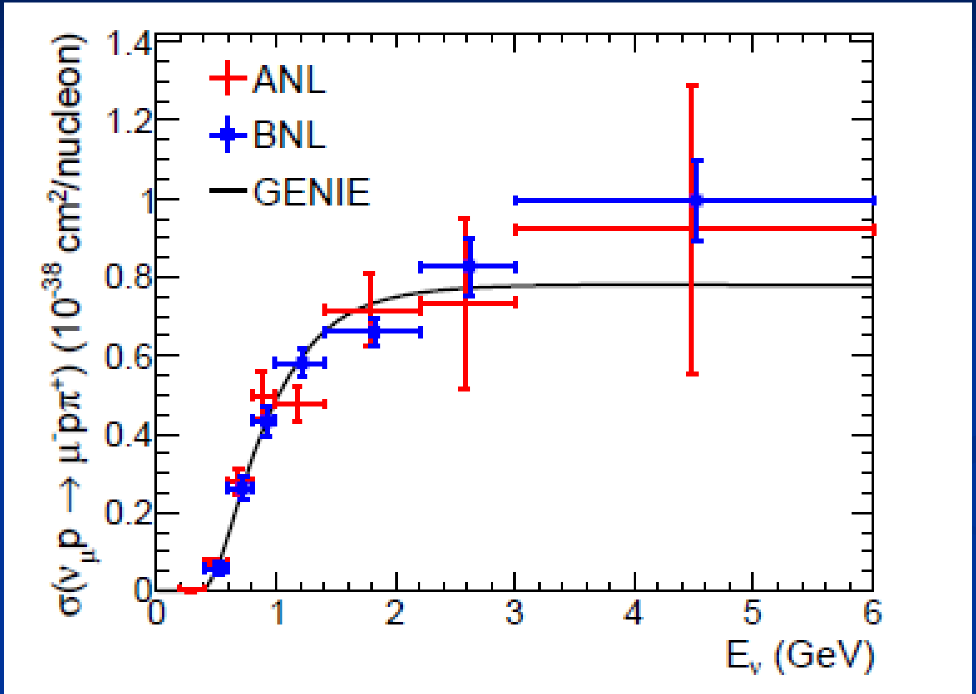
Pion production: Resonance

- pion production dominated by $P_{33}(1232)$ resonance:

$$J_\Delta^{\alpha\mu} = \left[\frac{C_3^V}{M_N}(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu) + \frac{C_4^V}{M_N^2}(g^{\alpha\mu}q\cdot p' - q^\alpha p'^\mu) + \frac{C_5^V}{M_N^2}(g^{\alpha\mu}q\cdot p - q^\alpha p^\mu)\right]\gamma_5$$
$$+\frac{C_3^A}{M_N}(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu) + \frac{C_4^A}{M_N^2}(g^{\alpha\mu}q\cdot p' - q^\alpha p'^\mu) + C_5^A g^{\alpha\mu} + \frac{C_6^A}{M_N^2}q^\alpha q^\mu$$

- C^V from electron data (MAID analysis with CVC)
- C^A from fit to neutrino data (experiments on hydrogen/deuterium), so far only C^A_5 determined, for other axial FFs only educated guesses

Pion Production



Reanalysis of BNL data (posthumous flux correction) by T2K group:
C.Wilkinson et al,
Phys.Rev. D90 (2014) no.11, 112017

Agrees with earlier findings in
Graczyk et al, Phys.Rev. D80 (2009) 09300
Lalakulich et al, Phys.Rev. D82 (2010) 093

10 – 15 % uncertainty in pion production cross sections

First Conclusion

- Uncertainties on elementary cross sections are (too) large
- Need new data on H and D to pin down the elementaries
- Data in the BNB would give info on QE and pion production

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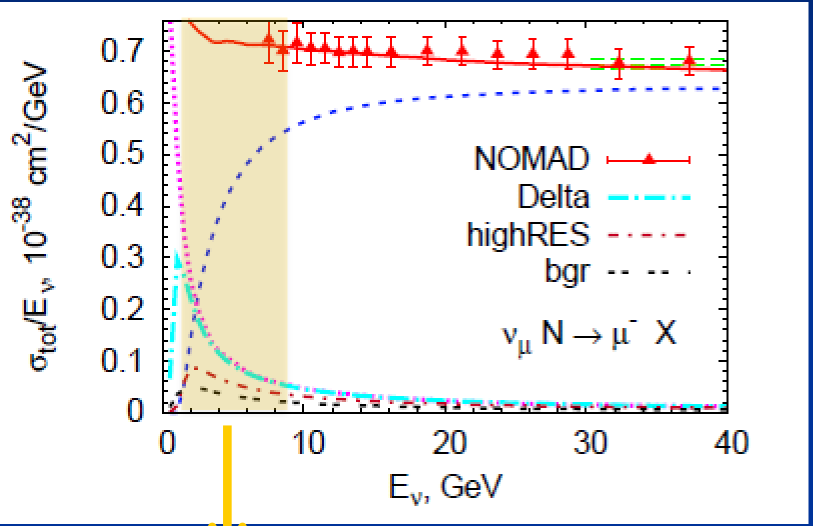
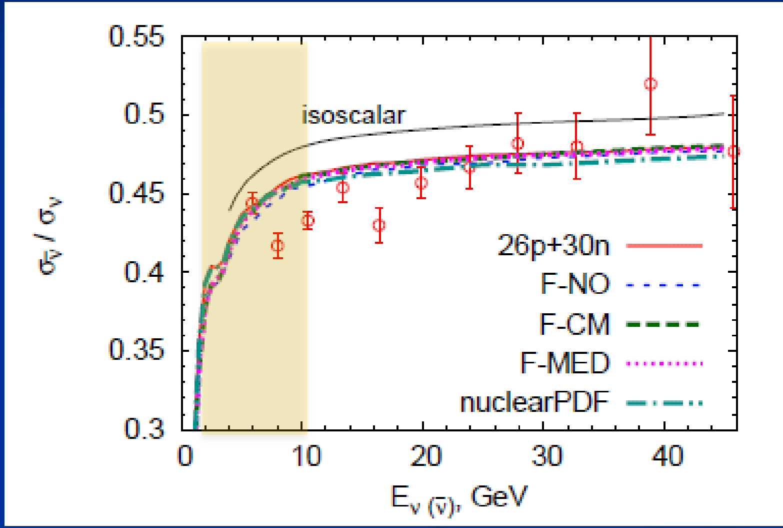
SIS – DIS by PYTHIA





Shallow Inelastic Scattering,
interplay of different reaction mechanisms
→ Ambiguity to switch from one mechanism to the other

Lalakulich et al, Phys.Rev. C86 (2012) 014607,
recently measured by MINERvA

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2p-2h Interactions

- **Assume**: 2p2h transverse, structure function W_1 for electrons from experimental fit of MEC contribution by Bosted and Mamyan (arXiv:1203.2262) and Christy (priv. comm.) to world data for $0 < W < 3.2$ GeV and $0.2 < Q^2 < 5$ GeV^2

$$\frac{d\sigma}{d\Omega dE'} = \frac{4\alpha^2}{Q^4} E'^2 2 \left(\frac{Q^2}{2\vec{q}^{\,2}} \cos^2\frac{\theta}{2} + \sin^2\frac{\theta}{2} \right) W_1(Q^2, \omega)$$

- Transversity established around 1990, Ericsson, Marteau

2p2h excitations: from electrons to neutrinos

- 2p2h: purely transverse, response from e-scattering

$$\frac{d\sigma}{d\Omega dE'} = \frac{G^2}{2\pi^2}E'^2\left[\frac{Q^2}{\vec{q}^{\,2}}\left(G_M^2\frac{\omega^2}{\vec{q}^{\,2}}+G_A^2\right)R_{\sigma\tau}(T)\cos^2\frac{\theta}{2}\right.$$
$$+2\left(G_M^2\frac{\omega^2}{\vec{q}^{\,2}}+G_A^2\right)R_{\sigma\tau}(T)\sin^2\frac{\theta}{2}$$
$$\left.\pm 2\frac{E+E'}{M}G_A G_M R_{\sigma\tau}(T)\sin^2\frac{\theta}{2}\right]$$

from: Martini et al.

$R_{\sigma\tau} \sim W_1$ from electron scattering

Same transverse response in V + A as in $V \cdot A \sim W_1$, Walecka 1975

Energy Reconstruction

- Kinematical (QE) method: use only properties of outgoing lepton. Lepton can be measured well, BUT
  - Problem: identify QE in nuclear environment
- Calorimetric method: use energies of all outgoing particles, BUT
  - Problem: detector thresholds and efficiencies
    Provide websites with these thesholds for each experiment!

➔ Have to correct ‚measured' energies by means of a generator

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Generators describe νA interactions?

- Take your favorite neutrino generator (GENIE, NEUT, …):
  „a good generator does not have to be right, provided it fits the data"

- Generators are indispensible for detector geometry effects!

- Generators have a long history, so long, that some of their contents have become forgotten, or are out-dated

νA Reaction

- General structure: **approximately** factorizes

full event (four-vectors of all particles in final state)

$\cong$

initial interaction *x* final state interaction

Determines inclusive X-section

Determines the final state particles

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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **GiBUU** : **Theory and Event Generator**
  based on a BM solution of Kadanoff-Baym equations
- **GiBUU** describes (within the same unified theory and code)
  - heavy ion reactions, particle production and flow
  - pion and proton induced reactions
  - low and high energy photon and electron induced reactions
  - neutrino induced reactions

……..using the same physics input! And the same code!

→ Perfect test for final state interactions

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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- GiBUU was constructed with the aim to encode the „best“ possible theory
- Initial interactions
  - Mean field potential with local Fermigas momentum distribution, nucleons are bound (not so in generators!)
  - Initial interactions are calculated by summing over interactions with all bound, Fermi-moving nucleons

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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- *Final state interaction:* propagates outgoing particles through the nucleus using *quantum-kinetic transport theory*, not just MC
- Fully relativistic. Initial and final interactions come from the same Hamiltonian. → Consistency of inclusive and semi-inclusive X-sections
- Calculations give the final state phase space distribution of all particles, four-vectors of all particles → generator

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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **GiBUU : Quantum-Kinetic Theory and Event Generator**
  based on a BM solution of Kadanoff-Baym equations
- Physics content and details of implementation in:
  Buss et al, Phys. Rept. 512 (2012) 1- 124
  Mine of information on theoretical treatment of potentials, collision terms, spectral functions and cross sections, useful for any generator
- Code from gibuu.hepforge.org, new version GiBUU 2016
  Details in Gallmeister et al, Phys.Rev. C94 (2016) no.3, 035502

Quantum-kinetic Transport Theory

On-shell drift term

Off-shell transport term

Collision term

$$\underbrace{\mathcal{D}F(x,p)}_{\text{On-shell drift term}} \underbrace{- \operatorname{tr}\left\{\Gamma f, \operatorname{Re}S^{\mathrm{ret}}(x,p)\right\}_{\mathrm{PB}}}_{\text{Off-shell transport term}} = \underbrace{C(x,p)}_{\text{Collision term}} \; .$$

$$\mathcal{D}F(x,p) = \{p_0 - H, F\}_{\mathrm{PB}} = \frac{\partial(p_0 - H)}{\partial x}\frac{\partial F}{\partial p} - \frac{\partial(p_0 - H)}{\partial p}\frac{\partial F}{\partial x}$$

H contains mean-field potentials

Describes time-evolution of *F(x,p)*

$$F(x,p) = 2\pi g f(x,p)\, \mathcal{P}(x,p)$$

Spectral function

Phase space distribution

KB equations with BM offshell term

GiBUU vs Generators

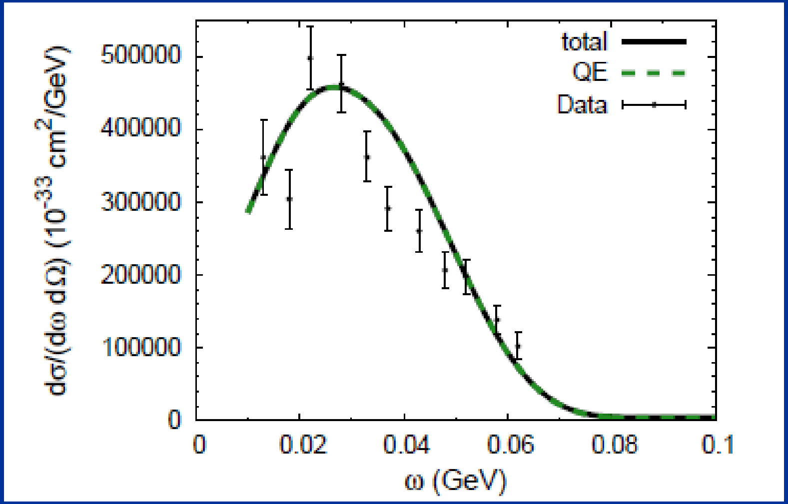
- Pros:
  - GiBUU has potentials for nucleons and hadrons, nuclei are bound
  - It is consistent: same groundstate for all processes
  - It has same potentials in first interactions and fsi
  - It follows phase-space distributions and spectral functions of hadrons throughout the nuclear volume (off-shell transport)
  - It is based on present-day‘s nuclear theory
- Cons:
  - GiBUU does not describe any coherent processes
  - GiBUU does not contain any detector geometry effects

Inclusives

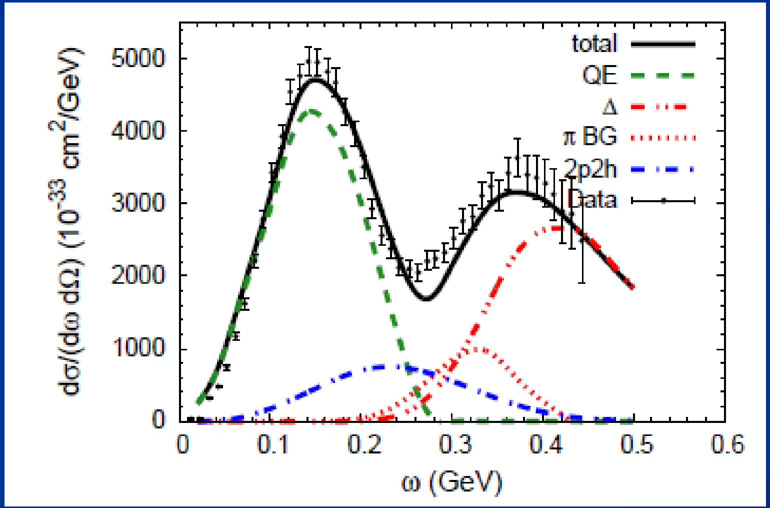
- Necessary Test: inclusive electron data

Inclusive QE Electron Scattering

- a necessary check for any generator development



0.24 GeV, 36 deg, $Q^2 = 0.02\ GeV^2$

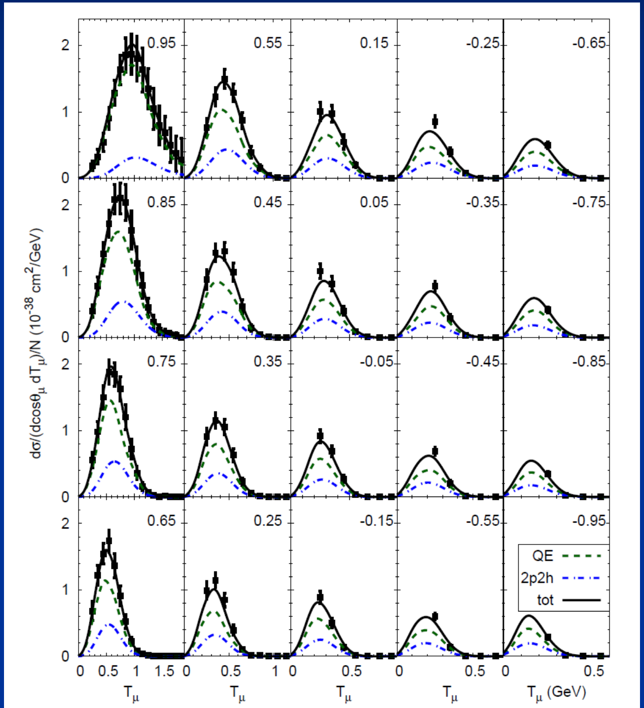


0.56 GeV, 60 deg, $Q^2 = 0.24\ GeV^2$

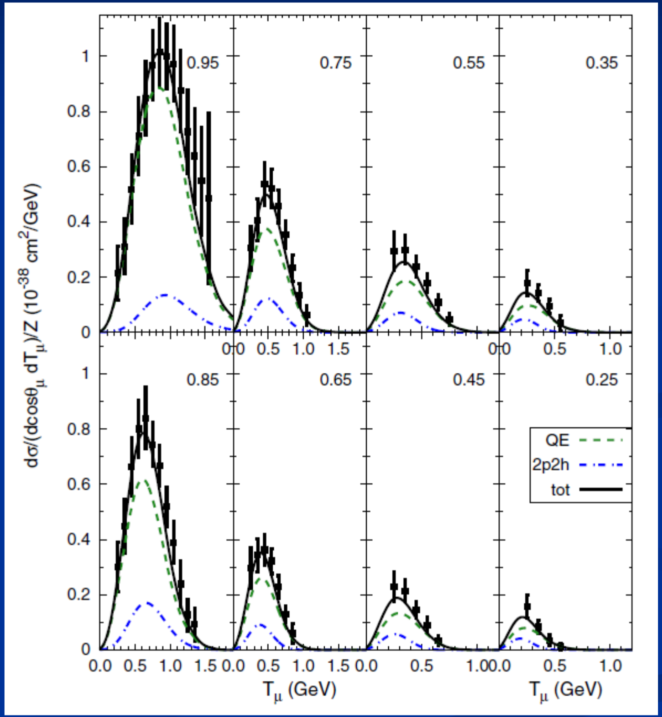
Now Neutrinos

- Test with data for muon and electron neutrinos, at different energy regimes
- Test for both QE and pion production
- NO tune, all results obtained with code ‚out of the box'

Inclusive 0-Pion Data (MiniBooNE)



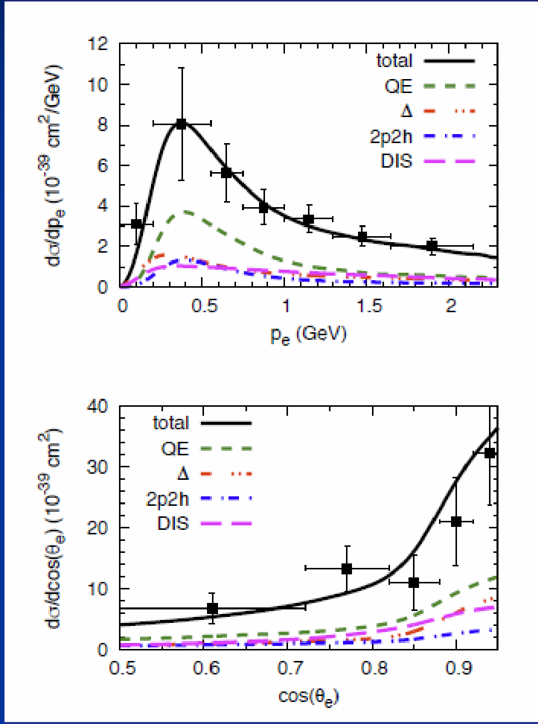
neutrino

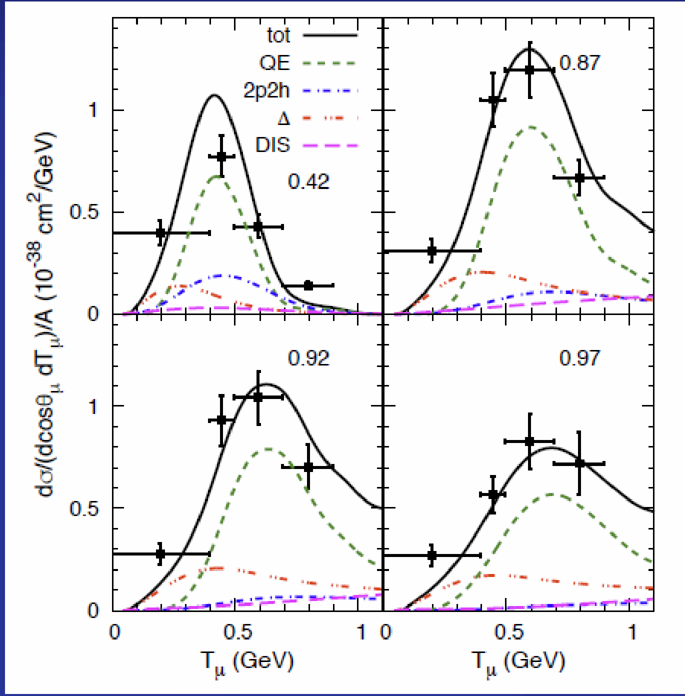


antineutrino

Comparison with T2K incl. Data

T2K, ν_e

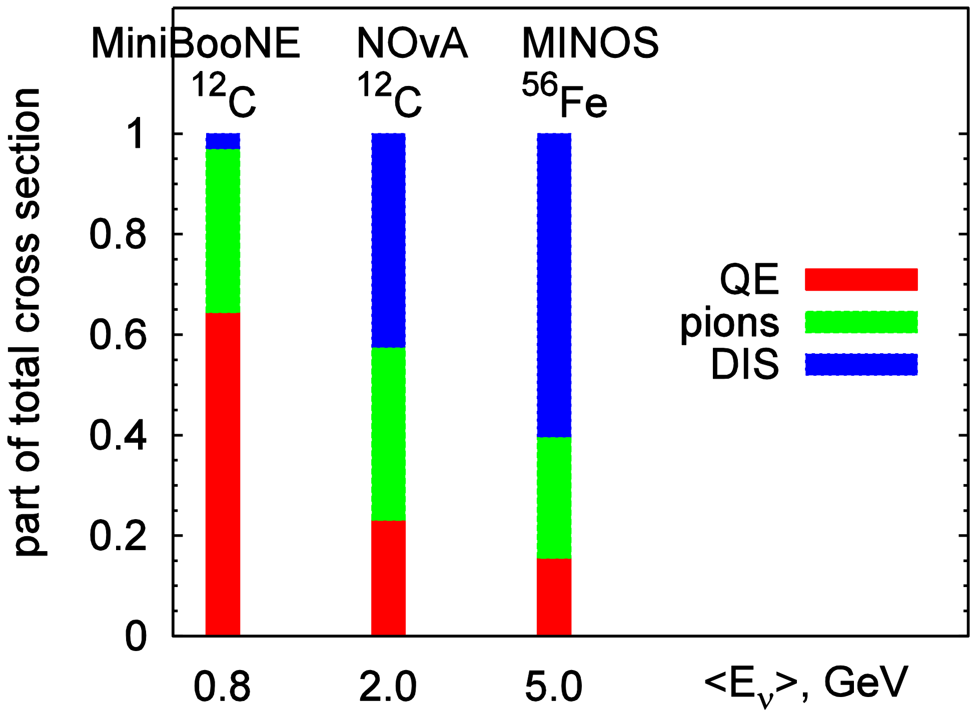




T2K, ν_μ

Agreement for different neutrino flavors

Reaction Channels



Pions

- Pions are an essential part of the cross section
  - For total signal
  - For ‚zero-pion' events

- → Pions have to be under control!

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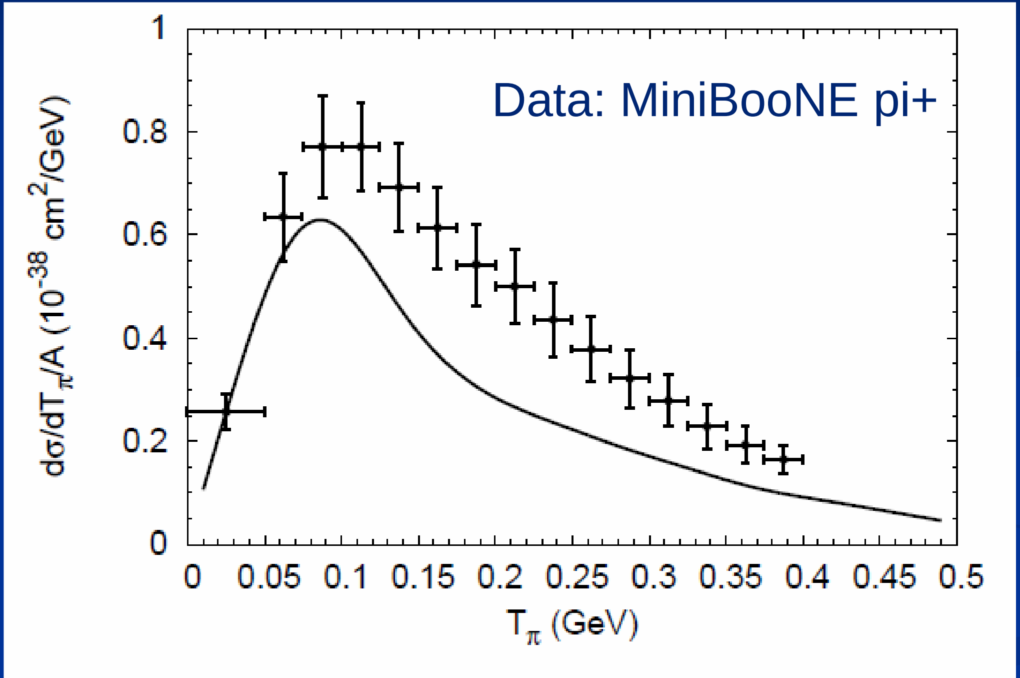
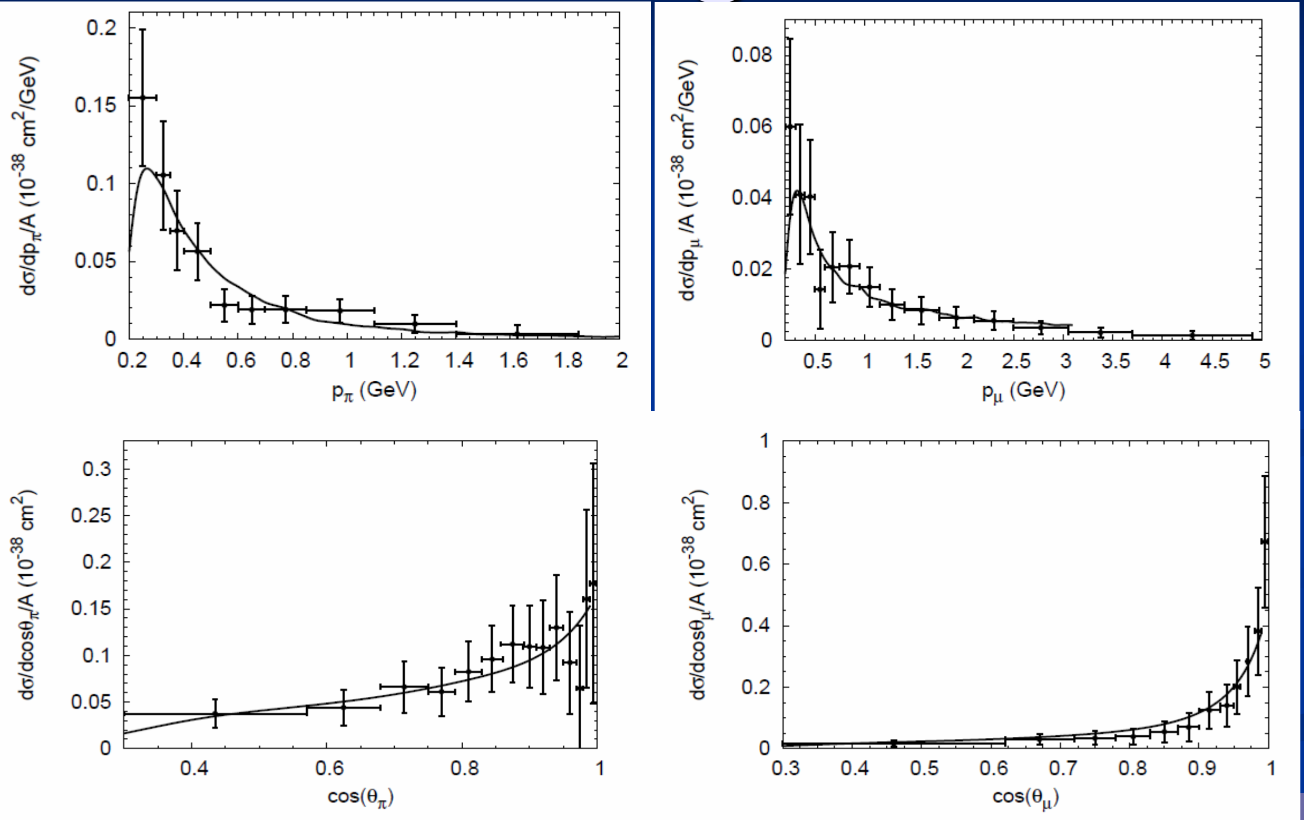
Pions: an essential part of total interactions



Major discrepancy: both magnitude and shape are wrong!

BIG PUZZLE!

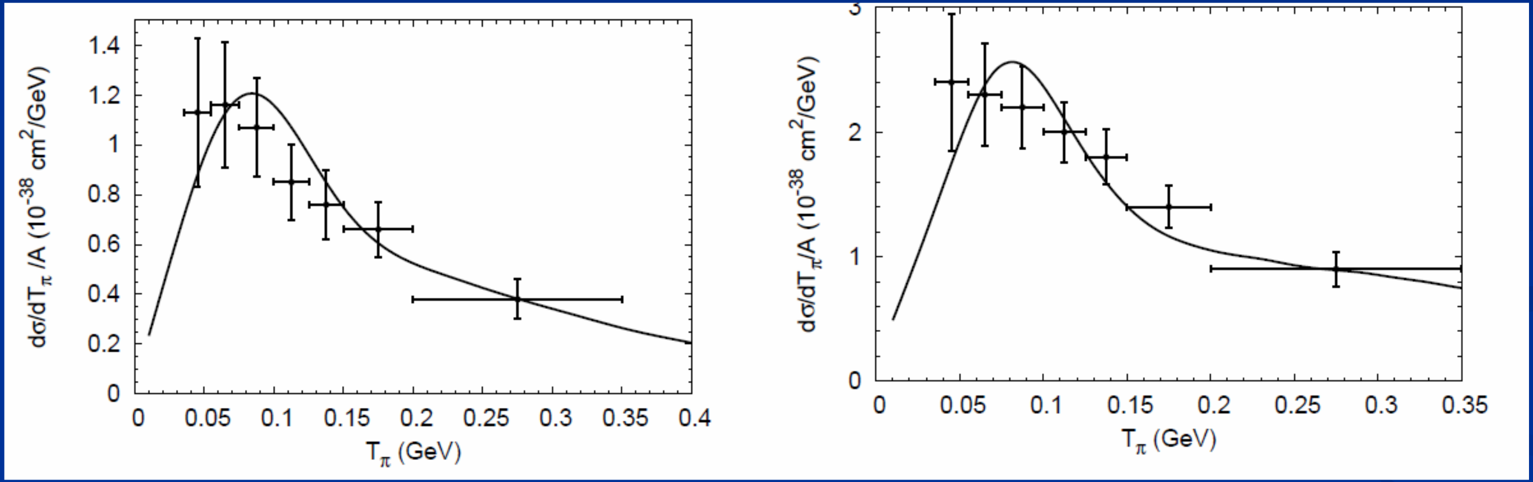
Pions at lower energies: T2K ND280



H_2O

Pions at higher energies: MINERvA

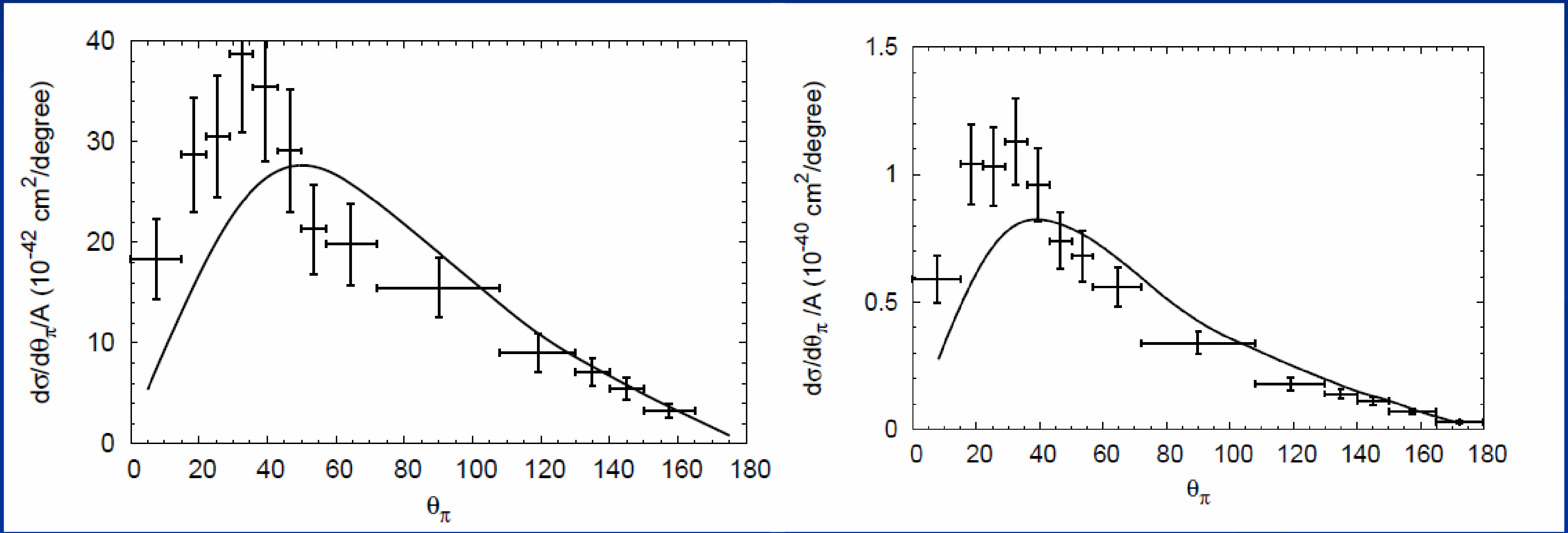
CC charged pions



W < 1.4 GeV
Eberly et al

W < 1.8 GeV, multiple pions
McGivern et al

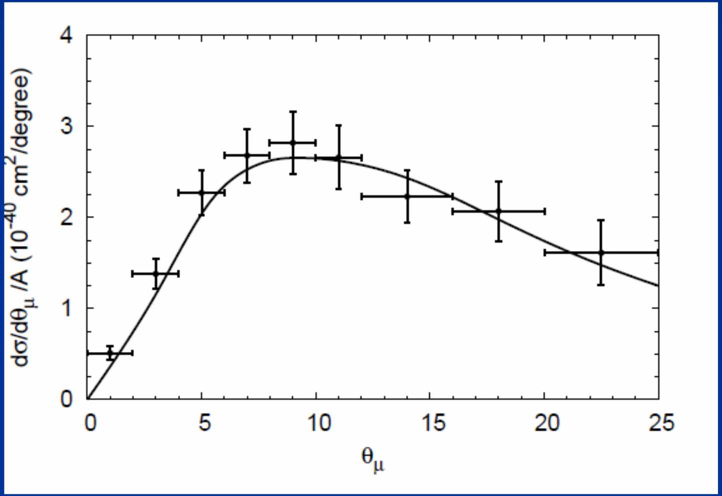
MINERvA

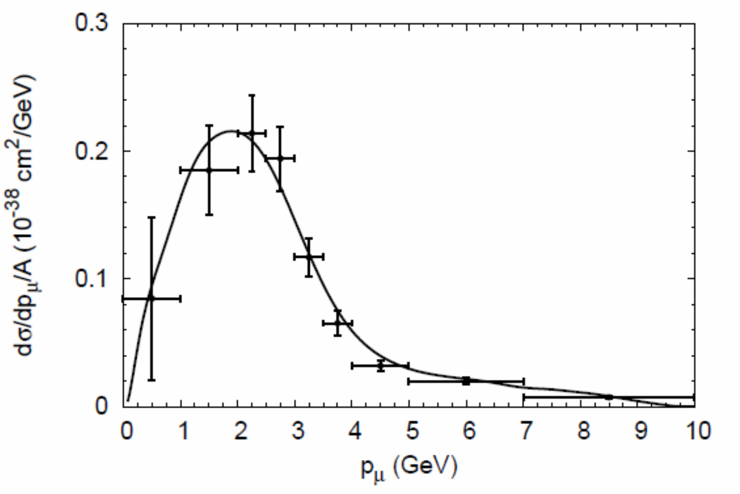


W < 1.4 GeV

W < 1.8 GeV

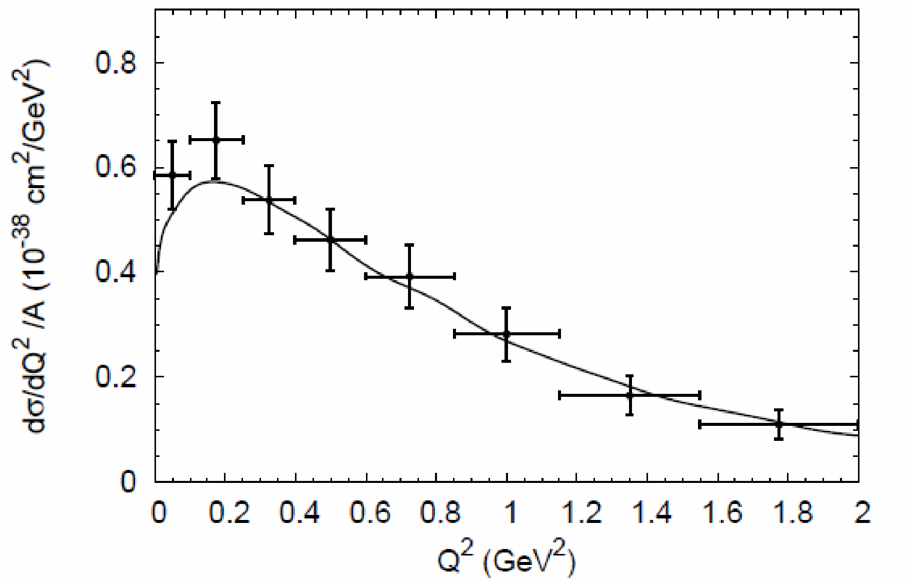
MINERvA Pions





W < 1.8 GeV

MINERvA-Pions



W < 1.8 GeV

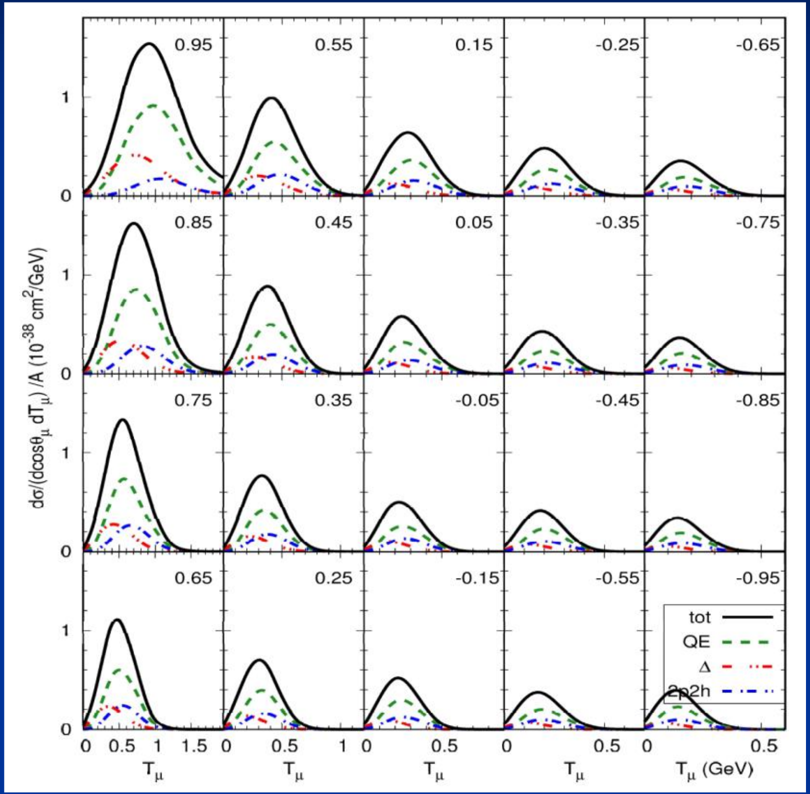
Discrepancies at

- Small Q^2
- Small pion angles
- Small pion momenta

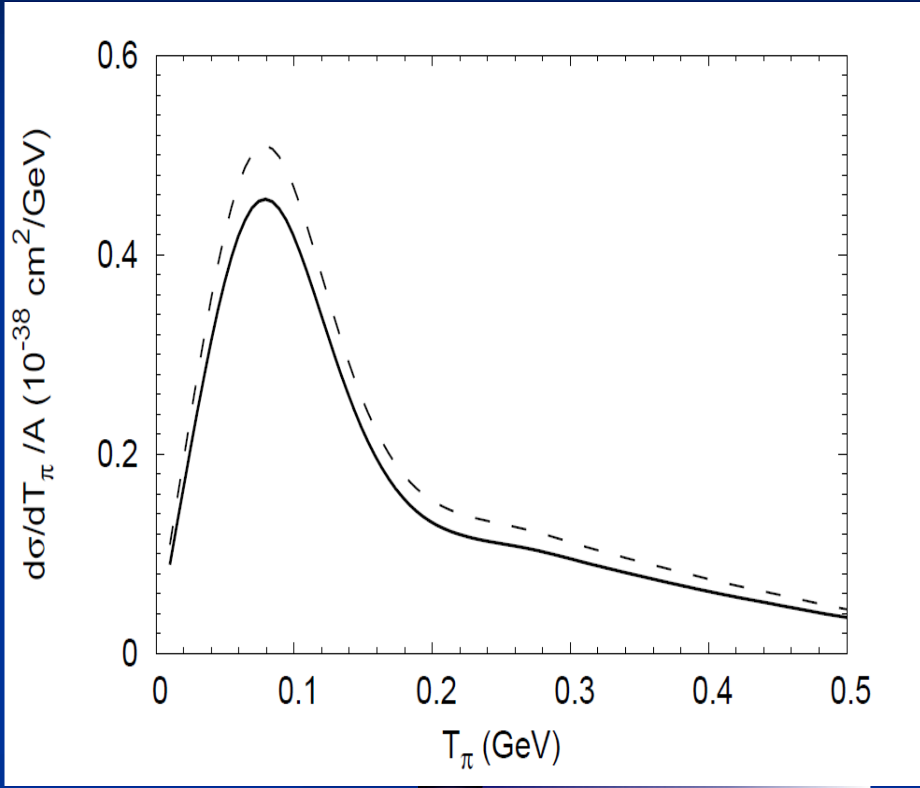
Coherent Contribution

Now Predictions

MicroBooNE

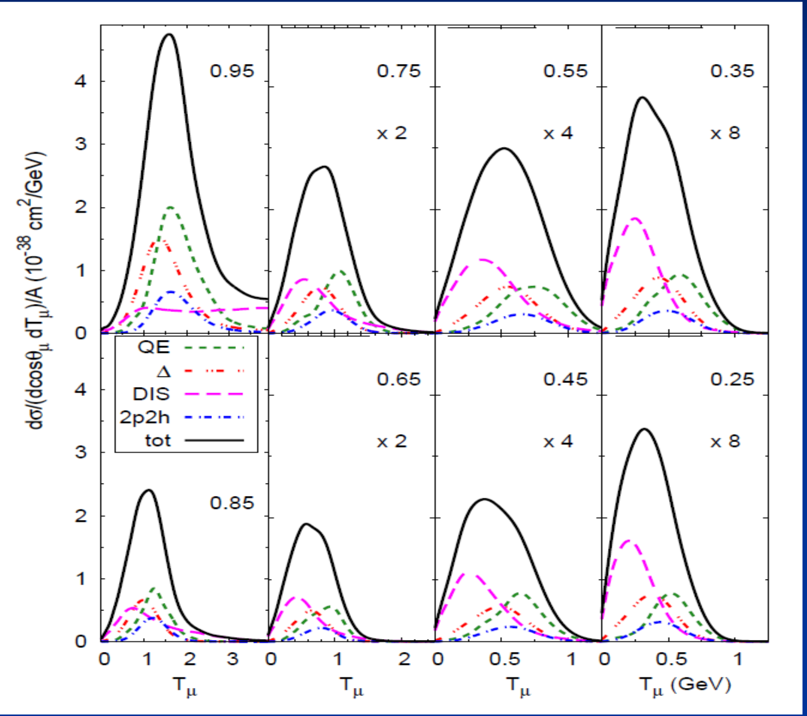


0.95
0.55
0.15
-0.25
-0.65
0.85
0.45
0.05
-0.35
-0.75
0.75
0.35
-0.05
-0.45
-0.85
0.65
0.25
-0.15
-0.55
-0.95
tot
QE
Δ
2p2h
$d\sigma/(d\cos\theta_\mu\, dT_\mu)$ /A (10^{-38} cm^2/GeV)
T_μ
T_μ (GeV)

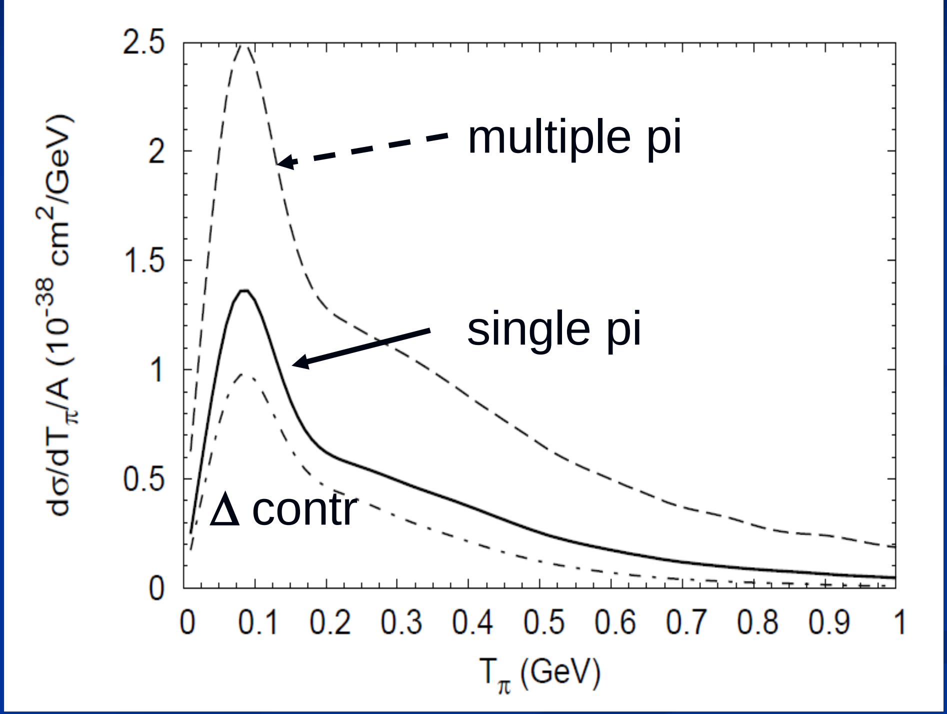


$d\sigma/dT_\pi$ /A (10^{-38} cm^2/GeV)
T_π (GeV)

NOvA



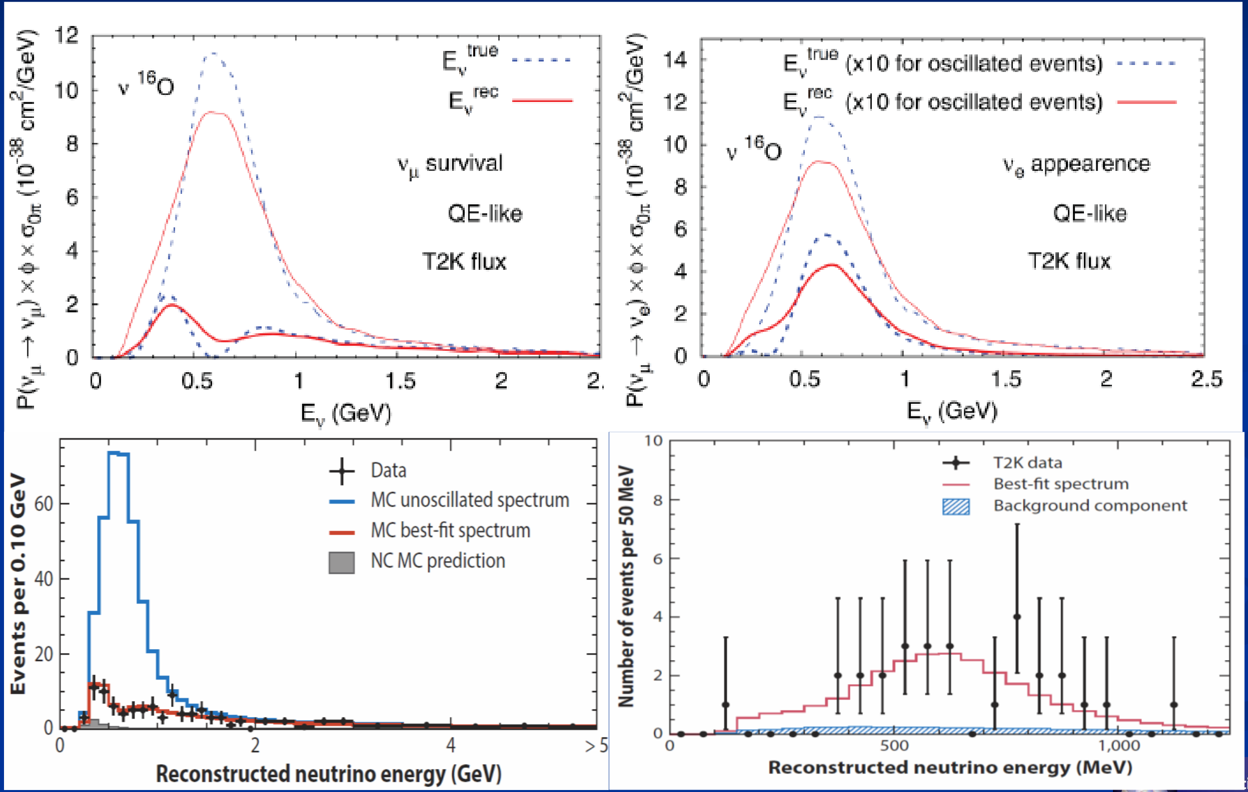
0.95
0.75
x 2
0.55
x 4
0.35
x 8
0.85
0.65
x 2
0.45
x 4
0.25
x 8
QE
Δ
DIS
2p2h
tot
$d\sigma/(d\cos\theta_\mu\, dT_\mu)/A\ (10^{-38}\ \mathrm{cm}^2/\mathrm{GeV})$
T_μ
T_μ (GeV)



multiple pi
single pi
Δ contr
$d\sigma/dT_\pi/A\ (10^{-38}\ \mathrm{cm}^2/\mathrm{GeV})$
T_π (GeV)

Now Influence on Oscillations

Oscillation Signals as $F(E_\nu)$



GiBUU

From:

Diwan et al.

Sensitivity of T2K to Energy Reconstruction

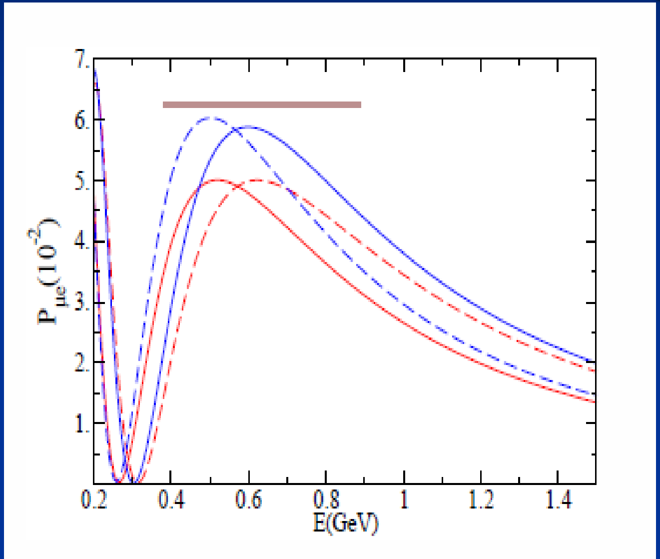
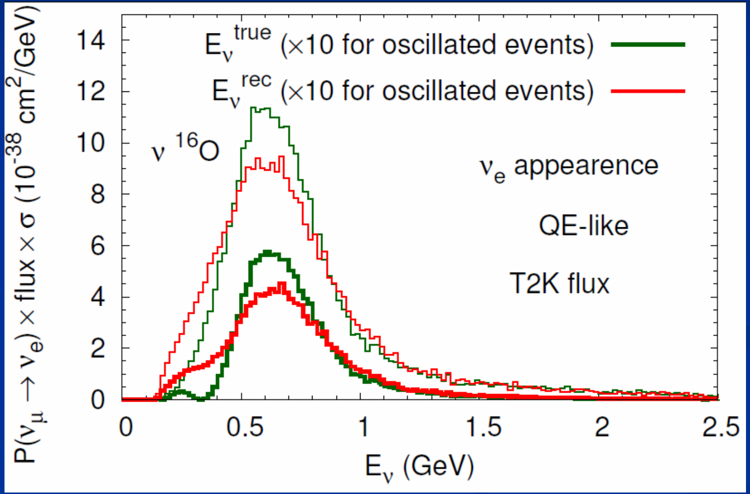
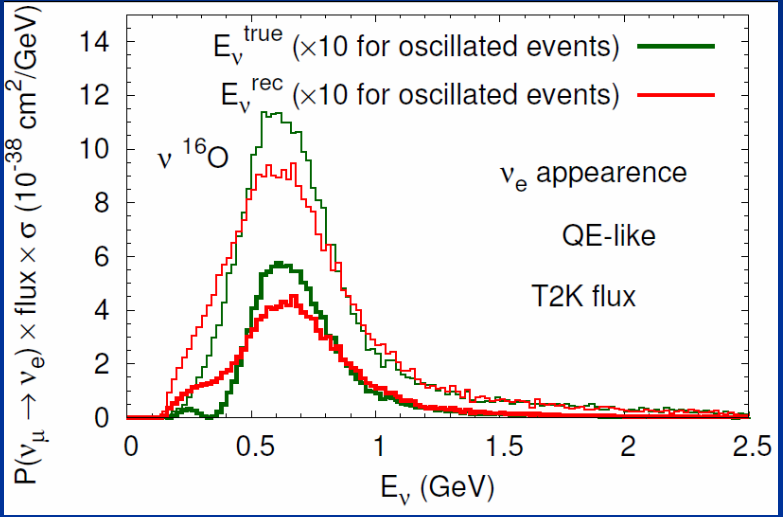


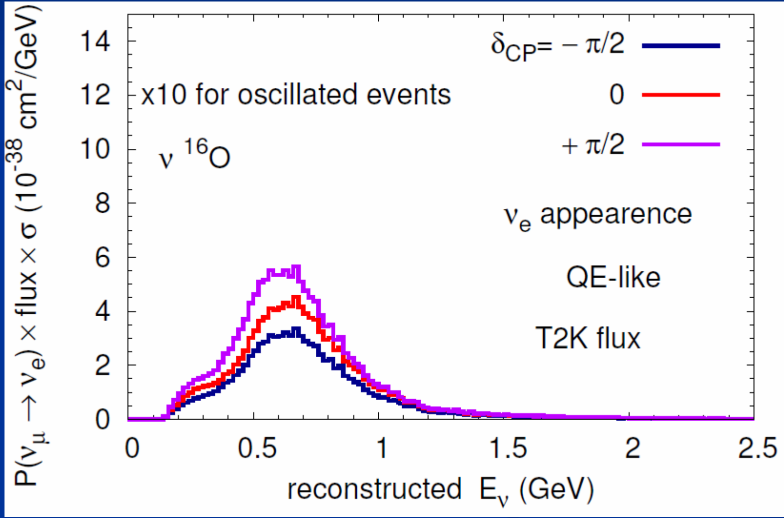
Fig. 2. $\mathcal{P}_{\mu e}$ in matter versus neutrino energy for the T2K experiment. The blue curves depict the normal hierarchy, red the inverse hierarchy. Solid curves depict positive θ_{13}, dashed curves negative θ_{13}



D.J. Ernst et al., arXiv:1303.4790 [nucl-th]

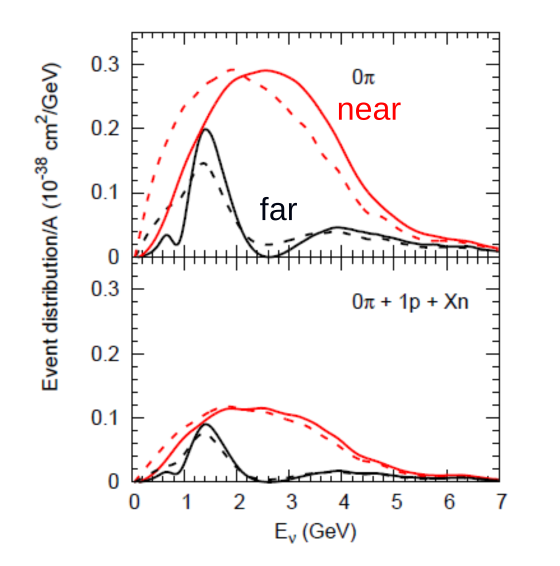
Oscillation signal in T2K
δ_{CP} sensitivity of appearance exps



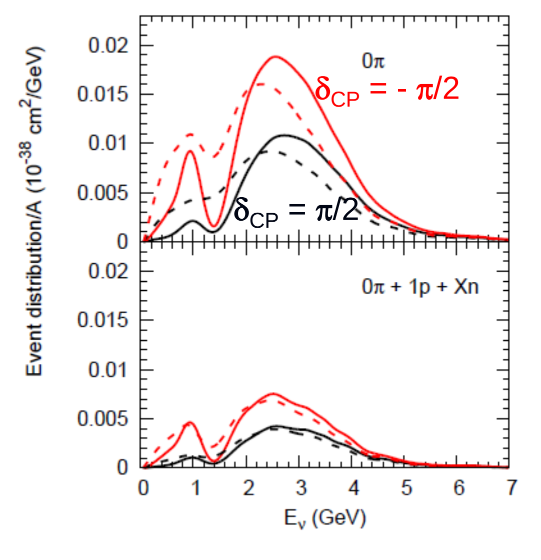


Uncertainties due to energy reconstruction as large as δ_{CP} dependence

Proton Tagging and Multi-Nucleons



Event rates at near (LBNF) and far detector (DUNE)



δ_{CP} sensitivity at DUNE

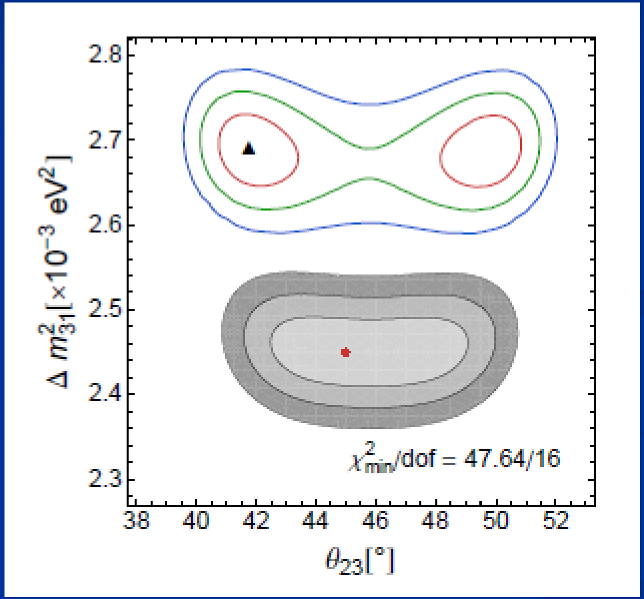
Mosel et al,
Phys.Rev.Lett. 112 (2014) 151802

Solid: true E
Dashed: reconstructed E

Generator Dependence of Oscillation Parameters

GiBUU-GENIE

GiBUU-GiBUU



From: P. Coloma et al, Phys.Rev. D89 (2014) 073015

Nature: GiBUU
Generator: GENIE

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Summary I

- Neutrino energy must be known within about 50 (T2K) or 100 (DUNE) MeV
- Neutrino energy must be reconstructed from final state observations
- Nuclear effects complicate the energy reconstruction
- The larger the step from reconstructed to true energies, the larger is the uncertainty in the oscillation parameters
  → Need good Nuclear Theory

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Summary II

- Quantum-kinetic Transport Theory is the (well established, and – in other fields of physics - widely used) method to deal with potentials and binding in non-equilibium processes, allows for off-shell transport
- GiBUU is an implementaton of transport theory
- GiBUU describes, without any tune:
  - Double-differential 0-pion data from MiniBooNE, neutrino and antineutrino
  - Fully inclusive T2K ND280 data for mu- and electron-neutrinos
  - Pions at T2K (water) and MINERvA
- GiBUU does not describe the MiniBooNE pion data: the puzzle remains!

What is needed?

- Need reaction studies on *nuclear targets* (MINERvA, T2K ND, NOvA ND, ANNIE, ..) to control many-body effects and fsi
- Need data without ‚generator contamination‘:

  e.g.: no flux cuts, no W cuts, no special reaction mechanism
- Need theory for full events, not just fully inclusive.
- Need a dedicated theory support program and a computational physics effort to construct a new, reliable generator for the precision era of neutrino physics

GiBUU

- Essential References:
  1. Buss et al, Phys. Rept. 512 (2012) 1
     contains both the theory and the practical implementation of transport theory
  2. Gallmeister et al., Phys.Rev. C94 (2016), 035502
     contains the latest changes in GiBUU2016
  3. Mosel, Ann. Rev. Nucl. Part. Sci. 66 (2016) 171
     short review, contains some discussion of generators
  4. Mosel et al, arXiv:1702.04932
     pion production comparison of MiniBooNE, T2K and MINERvA

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